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Comparison of Pullout Strength According to Thread Design of Pedicle Screw Under Various Bone Quality Circumstance

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Abstract

Comparison of Pullout Strength According to Thread Design of Pedicle Screw Under Various Bone Quality Circumstance

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Although dual-threaded pedicle screw has been developed, the potential advantages over a conventional single-threaded pedicle screw still remains controversial. The purpose of the study was to investigate the biomechanical performance of dual-threaded pedicle screws by comparing pullout strength with single-treaded screw using polyurethane foams and finite element (FE) models. We designed four types of pedicle screws with different thread patterns. They were, Type I: single thread screw (conventional single-threaded screw); Type II: double threads screw; Type III: dual-threaded screw with double threads in proximal one-fourth; and Type IV: dual-threaded screw with double threads in proximal and distal one-fourths (newly designed double dual-threaded screw).

Five types of polyurethane foam blocks simulating various bone quality were, Type A: cancellous bone; Type B: cancellous bone with cortical bone in upper margin; Type C: osteoporotic cancellous bone; Type D: osteoporotic cancellous bone with cortical bone in upper margin; and Type E: osteoporotic cancellous bone with cortical bone in upper and lower margin. To perform comparison in normal quality and osteoporotic bone, Type A, B, C and D specimens were used to compare pullout strength among Type I, II, and III screws. To perform comparison in osteoporotic bone with and without cortical bone, Type C and E were used for comparisons among Type I, II, and IV screws. Concurrently, 3-dimensional (3D) FE models simulating the biomechanical test were created to predict their pullout strength. In experimental tests, compared to conventional single-threaded pedicle screw, dual-threaded pedicle screws exhibited higher and significantly lower pullout strength in normal quality and compromised osteoporotic bone, respectively. With the trend of statistical significance, the double dual-threaded pedicle screw exhibited better biomechanical performance in osteoporotic bone with bicortical bone. The results of FE model analysis corresponded to those of experimental tests, indicates that FE analysis is a reliable tool in investigating pedicle screw pullout biomechanics.

Keywords: pedicle screw; pullout strength; dual-threaded; polyurethane foam block; finite element model

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제 1 장 서　　론

제 1 절 연구의 배경

It is well known that pedicle screw can provide the robust initial stability to a spinal segment, which can facilitate critical support during fusion surgeries for various spinal diseases [1-4]. Accordingly, the pedicle screw has been widely used in fusion surgery for degenerative spinal disease. However, the versatile use of the pedicle screw is limited by fixation failure result from screw loosening, the incidence of which was reported to be 0.6-11% and might be even higher in the patients with osteoporosis [5,6].

As the general population continues to grow older, spine surgeons frequently encounter the challenging cases in which patients not only present with osteoporotic spine, but also require pedicle screw fixation for successful surgical treatment. The materials of the pedicle screw, such as stainless steel, titanium alloy, nickel-titanium (NiTi) alloy, may potentially cause corrosion and release some harmful metallic ions to human body [7-9]. In order to improve corrosion resistance and fixation capability, a growing number of coating techniques were used for biomedical applications [10-12]. In addition, because the compromised bone quality caused by osteoporosis increases the risk of an early fixation failure such as screw loosening, several ways for enhancing device fixation have been explored, including alterations of screw thread design, optimization of pilot hole size for non-self-tapping screws, modification of the implant’ s trajectory, and bone cement augmentation [13].

Pedicle screw with dual thread has been developed for mechanical improvement of pedicle screws by two different threads: a proximal fine pitch for the proximal shaft within pedicle, and a distal standard single coarse pitch for cancellous bone. The potential advantage of pedicle screws with two different threads is supported by previous studies [14,15]. However, some researchers suggest that the dual-threaded design did not yield any additional advantage over a single thread, as a cylindrical single-lead thread screws presented better biomechanical anchorage than the dual-lead thread screws in axial loading conditions [14]. Therefore, selection of optimal thread design for improvement of device fixation in clinical practice remains controversial. Because of increased resistance force to pullout in pedicle region, we hypothesized that the screws with dual-threaded design would exhibit better biomechanical performance over a single-threaded screw in terms of pullout strength.

제 2 절 연구의 목적

The purpose of present study was to investigate the biomechanical performance of dual-threaded pedicle screws by comparing pullout strength with single-treaded screw in various bone quality circumstance using laminated polyurethane foam blocks and finite element (FE) models.

제 2장 본　　문

제 1 절 연구방법

Experimental study

Types of the pedicle screws

The screws used in this study were of uniform dimensions in length, outer diameter, proximal and distal core diameter, with a value of 40mm, 4.5mm, 4.0mm and 2.7mm, respectively (**Table 1**). Four types of screws with different thread patterns were designed to test the axial pullout strength. All pedicle screws were made of stainless steel material (**Figure 1**).

Type I: single−threaded pedicle screw;

Type II: double threads screw (control type);

Type III: dual−threaded screw;

Type IV: newly designed double dual−threaded pedicle screw.

Preparation of specimens

The polyurethane foams have been commonly used as an alternative test medium analogous to human bone [16], and have shown several advantages compared to human vertebra, including reducing the inter−specimen variability of cadaveric bones and prevention of deformation or breakage during mechanical loading test [17]. Cellular polyurethane foams (Sawbones, Pacific Research Corporation, Vashon, Washington, USA), with three different densities were used as biomechanical testing material in this study. The foam with low density of 160 kg/m^3, middle density of 320 kg/m^3 and high density of 800 kg/m^3 represented for human osteoporotic cancellous bone, normal cancellous bone and cortical bone, respectively, in accordance with the American Society for Testing and Materials (ASTM F1839-01) protocol [16]. To simulate various circumstance of bone quality, five types of bone specimen were designed using various density of polyurethane foam blocks (**Figure 2**).

Type A: normal cancellous bone;

Type B: normal cancellous bone with cortical bone in the upper margin;

Type C: osteoporotic cancellous bone;

Type D: osteoporotic cancellous bone with cortical bone in the upper margin.

Type E: osteoporotic cancellous bone with cortical bone in the upper and lower margin.

To simulate screw insertion in normal quality and osteoporotic bone using conventional technique, Type A, B, C and D bone specimens with 50.8mm×50.8mm×40mm in size were used to compare pullout strength among Type I, II, and III screws (**Figure 2a**). To simulate the screw insertion in osteoporotic bone with and without cortical bone using anterior cortex purchase technique (**Figure 3**), bone specimens of Type C and E measuring 50.8mm×50.8mm×33mm, were used for comparisons among Type I, II, and IV screws (**Figure 2b**).

Test apparatus

The experimental configuration used for testing the axial pullout strength of pedicle screws conforms to requirements of a suitable axial loading test fixture guided by the ASTM F543-13 Standard Specification and Test Methods for Metallic Medical bone screws [18] and is shown in **Figure 4**. The pullout test machine (MTS MiniBionix 858, MTS systems Corp, Eden Prairie, MN, USA) consisted of a rigid frame with 130mm×100mm×100mm in size. It was fixed to the base of a load frame, with an opening in the upper surface where the screw can pass through. The test block with laminated polyurethane foam and screw inside was connected to the load frame. The load frame was transferred vertically through the head of the screw and was aligned with the longitudinal axis of the screw. The setup configuration was designed rigid enough so that deflection under the loading conditions was negligible. The pullout test was conducted according to the ASTM F543−13 Standard testing protocol [18].

Biomechanical testing procedures

A pilot hole with 2.7mm diameter was drilled manually at the center of a polyurethane block. Then the pedicle screw was inserted into the polyurethane block sample to the full depth, where the tip of the screw was leveled or passed through the bottom of the block depending on the size of the block. The foam block with pedicle screw inserted was completely seated within the rigid fixture frame, which was fixed to the base of the load frame. This design ensured that the direction of the applied load was aligned with longitudinal axis of the screw. An extraction load was gradually applied to the screw head at a loading rate of 5mm/ min, until the screw was pulled out from the test block. The peak load was defined as the screw pullout strength and the load−displacement curve was recorded using a data acquisition system (instruNet, GW Instruments, Somerville, MA, USA). The same biomechanical testing procedure was conducted five times per case and the pullout strength of all types of screws in different bone specimens was recorded for analysis.

FE model analysis

Finite element models simulation

Two three-dimensional (3D) models of Type I (conventional single-threaded screw) and Type III (dual-threaded screw) screw threads were developed. The geometrical details of the two models were based on the dimensions and profiles of predetermined thread design (**Figure 5a**). Meanwhile, two 3D models of cylindrical block simulating Type B (normal bone with cortical bone) and Type D (osteoporotic bone with cortical bone) bone specimens were built (**Figure 5b**). 3D geometrical surface of those models were generated by a software program (Mimics; Materialise Inc., Leuven, Belgium). The surface models from the Mimics software were transformed to solid models using Unigraphics NX 3.0 (Siemens PLM Software, Torrance, CA, USA). Then the solid models were imported into Hypermesh 8.0 (Altair Engineering, Inc., Troy, MI, USA) to generate FE meshes. FE model analysis was performed with commercially available software (ABAQUS 6.6-1; Hibbitt, Karlsson and Sorenson, Inc., Providence, RI, USA). The two types of screw were inserted into center of the cylindrical blocks with the same trajectory and full depth, simulating biomechanical testing condition. Material properties of the screws and bone specimens were selected according to previous literature sources [19–21] (**Table 2**). 3D homogenous and eight−noded isotropic solid elements were employed in this study. To simulate interface contacts between the screw threads and bone blocks, the surface−to−surface contact elements with a frictional coefficient of 0.2 were applied [22]. The final bone−screw FE model contained 339026 elements and 72701 nodes.

Boundary and loading conditions

Loading conditions of this FE investigation were corresponding to screw pullout test according to the ASTMF543−13standard protocol [18]. The nodes of the circumferential surface of the bone model were fixed in all directions, and an extraction loading condition was simulated at the end surface of the screw as axial tensile force. The pullout strength was defined as the maximum reaction force, which was extracted from all the restrained nodes at the end surface of the screw during pullout. The stress distribution along the screw threads was analyzed during screw pullout procedure. The predicted pullout strength from the FE model analysis were compared with current experimental test and pervious experimental study for model validation [23].

Statistical analysis

Independent *t*−tests were performed to assess the significant differences of pullout strength between dual−threaded screws and conventional single−threaded screw in the same type of bone specimen. Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, version 20.0; SPSS, Inc., Chicago, IL, USA). A p value of <0.05 was considered statistically significant.

제 2 절 연구결과

Experimental study

All the screws were loaded to failure, and the structure of which was completely preserved after pullout. Defined as the experimentally measured peak load, the pullout strength of all types of screws is shown in **Table 3.**

Comparison among Type I, II, and III screws in Type A, B, C and D bone specimens (in normal and osteoporotic bone)

The typical patterns of the load−displacement curves, that illustrate the holding characteristics of different bone specimens combined with different screw type, are presented in **Figure 6a.** All the load–displacement curves exhibited similar trends that the load increased sharply as the screws were extracted, and then decreased rapidly once the screws were pulled out from the specimens. The displacement at the point of peak load was always less than 1.0mm. In Type A bone specimen which represent normal cancellous bone, the pullout strength required for Type I screw (conventional pedicle screw) was 2.23±0.07 KN and 2.28±0.13 KN for Type III screw (dual–threaded screw), and there was no significant difference (P=0.471). In Type B bone specimen which represent normal cancellous bone with cortical bone, the pullout strengths were 2.65±0.16 KN and 2.80±0.08 KN for Type I and Type III screws, respectively, and there was no significant difference (P=0.106). However, in Type C bone specimen which represent osteoporotic cancellous bone, the pullout strength required for Type III screw was 1.32±0.13 KN, which was significantly lower than it for Type I screw (1.56±0.23 KN) (P=0.046). Furthermore, in Type D bone specimen which represent osteoporotic cancellous bone with bicortical bone, Type III screw exhibited significant lower pullout strength (1.82±0.09 KN) compare to Type I screw (1.99±0.11 KN) (P=0.031) (Figure 7a).

Comparison among Type I, II, and IV screws in Type C and E bone *specimens (in osteoporotic bone with and without cortical bone)*

The typical load−displacement curves are shown in **Figure 6b**. The patterns of the load−displacement curves for all the screws exhibited similar trends as described in the above section. In Type C bone specimen which represent osteoporotic cancellous bone without cortical bone, the pullout strength for Type IV (double dual−threaded screw) (0.98±0.15 KN) was significantly lower than it for Type I screw (1.56±0.23 KN) (**P=0.006**). In Type E bone specimen which represent osteoporotic cancellous bone with cortical bone, Type IV screw exhibited higher pullout strength (2.67±0.07 KN) compare to Type I screw (2.54±0.15 KN), with the trend of statistical significance (P=0.105) (**Figure 7b**).

FE model analysis

Model validation

For model validation, the loading protocols of the simulated model were identical to those of current experimental study. The predicted pullout strength from normal and osteoporotic bone models corresponded to the results of current experimental test, and they were slightly higher than the range of values measured by Hashemi, et al. [23]. The discrepancy can be explained by the differences in bone specimen design between the two studies mainly, because the cortical bone margin was included in current FE models.

Comparison between Type I and Type III screws in normal and osteoporotic bone models

In normal bone model, the pullout strength of Type III screw was 2.37 KN, which was 17% higher than Type I screw (1.97 KN). However, in osteoporotic bone model, the pullout strength required for Type III screw (1.14 KN) was 30% lower than it for Type I screw (1.61 KN) (**Figure 7c**). During screw pullout procedure, both types of the screw exhibited similar stress distribution patterns along the screw threads, that the proximal and tip area of the screw exhibited high magnitude of Von Mises stress in both normal and osteoporotic bone model (**Figure 8**). In normal bone model, the maximum Von Mises Stress for Type I screw were 1.5 MPa and 5.8 MPa in cortical and cancellous bone, respectively; while for Type III screw, they were 1.3 MPa and 5.0 MPa, respectively. However, in osteoporotic bone model, the Type I screw yielded the max Von Mises Stress in cortical and cancellous bone area were 1.8 MPa and 4.8 MPa, respectively; while they were 2.1 MPa and 5.6 MPa for

Type III screw, respectively.

제 3 절 고찰

From the results of our study, we found that compared to a conventional pedicle screw, the dual-threaded pedicle screw exhibited higher and significant lower pullout strength in normal quality and osteoporotic bone, respectively, after controlling several factors such as screw length and diameter, and insertion technique. However, using anterior cortex purchase insertion technique, the newly designed double dual-threaded pedicle screw exhibited better pullout biomechanics in osteoporotic bone with bicortical bone.

Pullout strength of the pedicle screw, as one of important mechanism responsible for implant failure, has been widely used to assess the strength of bone- screw interface under different conditions [24,25], and is a popular biomechanical testing parameter. Several factors, including the size and design of the screw, pedicle structures, bone quality, size of pilot wholes, and insertion technique, may affect pullout strength of pedicle screw [13]. Therefore, these variable factors must be controlled under similar situation during experimental testing to ensure a reliable comparison of differently designed screws. Polyurethane foam blocks with consistent properties are used to simulate a particular the human bone density, and this commonly accepted testing material can limit the bias caused by the variation of human bone quality, pedicle structures, and screw-cortical interface [5]. Furthermore, the foam blocks, which are simple and easy to handle, could prevent deformation and breakage during biomechanical test [18]. Therefore, to investigate the biomechanical performance of differently designed pedicle screws, we used the laminated polyurethane foam blocks to compare the pullout strength in current experimental study.

Based on the result of our tests, we found that when compared to the conventional single-threaded screw (Type I), dual-threaded screw (Type III) exhibited better pullout strength in normal cancellous bones either with or without cortical bone (Type B and A bone specimens), although there were no significant differences. The pullout strength of the screw depends on several variables, and most of which are related to the biomechanical properties of the bone-screw interface along the length of the screw. With uniformed dimension in length, diameter, and thread profile of all screws in this study, the quality of bone and the thread pattern were the main factors affecting pullout strength of the screw [19,26]. As the normal cancellous bone contains high quality of bone, the thread pattern determining properties of the bone-screw interface was critical on holding strength of the pedicle screw. Because double threads part of the screw creates more properties of the bone-screw interface, the screws with larger double threads region may display higher purchase to resist the pedicle screw pullout in normal cancellous bone. This possibility was supported by the result of our test that full double threads screw (Type II) showed the highest pullout strength in normal cancellous bone with and without cortical bone (Type B and A bone specimens) (**Table 3**).

However, the biomechanical testing in osteoporotic bone model yielded different results. Compared to conventional single-threaded screw (Type I), the dual-threaded screw (Type III) showed significantly lower pullout strength in osteoporotic bone either with or without bicortical bone (Type D and C bone specimens). This finding is consistent with a previous study [27] reasoning that osteoporotic cancellous bone with fragile trabecular would be destroyed easily by the screw thread during insertion. Therefore, the screws with larger region of double threads would create more destroyed properties of the bone-screw interface, leading to decreased resistance to pullout force. This proposed mechanism may explain why the dual-threaded screw exhibited significantly lower pullout strength relative to conventional single-threaded screw in osteoporotic cancellous bone with and without cortical bone. A previous study is in concordance with the present results, which have reported that dual−threaded screws increase insertion torque in poor quality bone compared to single−threaded screw, without increasing axial pullout strength [15].

Notably, the cortical bone is less affected by osteoporosis relative to cancellous bone [28], and 60% of pullout strength was provided by cortical bone in the pedicle region [15]. Therefore, we designed the double dual−threaded screw with double threads in both proximal and distal margin to augment the holding strength in pedicle and anterior cortex of vertebral body region. To simulate the screw insertion in real vertebral body using anterior cortex purchase technique (**Figure 3**), we used the foam block with smaller size (Type C and E bone specimens), in which the tip of the screw could pass through the bottom. Although the cancellous bone may experience much more destruction during insertion of the screw with double threads, the interaction of cortical bone with double threads in proximal and distal area could provide enhanced holding power and thus resist pullout. That may explain why the double dual−threaded screw (Type IV) exhibited higher pullout strength in osteoporotic bone with bicortical bone (Type E bone specimen), compared to conventional single−threaded screw (Type I).

Although there was no significant difference because of small sample size, the trend of statistical significance indicates that the biomechanical performance of the double dual-threaded screw would be potentially superior to conventional pedicle screw. This finding is different from those of previous studies investigating biomechanical performance of sing and dual-threaded screw under axial loading condition [14,15].

The results of the present experimental study were different from our hypothesis, that the dual-threaded pedicle screw exhibited significant lower pullout strength in osteoporotic bone compared to the conventional single-threaded screw. To better conform the experimental test, we developed normal and osteoporotic bone models with cortical margin to perform comparison among screws with different thread design under axial loading condition. FE model analysis, as a convenient, low-cost and less time consuming tool, has been widely used in studies investigating biomechanical performance of pedicles screws [5,19]. With computational engineering methods, effects of multiple factors can be controlled or simulated in FE model analysis for biomechanical prediction. From the results of FE model analysis, we found that the maximum Von Mises Stress was negatively correlated to pullout strength, because the bone-screw interface region with lower magnitude of stress plays more important role in stabilizing the pedicle screw leading to increased resistance to pullout. Furthermore, the predicted pullout strength corresponded to the findings from current experimental test, which indicates that FE analysis is a reliable tool in investigating and predicting pedicle screw pullout biomechanics. Additional FE studies are needed to refine and further validate the predictive value of these FE models under different loading conditions, such as toggling, cyclic loading conditions.

Although a growing number of spinal surgeries are using dual-threaded screw as fixation devices to improve fixation capability for osteoporotic patients, the prioritization of these devices over conventional pedicle screw remains controversial. According to the result of our study, the dual-threaded pedicle screw exhibited significantly lower pullout strength in osteoporotic bone, which indicates that they would not be the optimal fixation devices for osteoporotic patients. However, promoted biomechanical performance of the double dual-threaded screw in osteoporotic cancellous bone with bicortical bone margin indicates that this device could be an alternative option to patients with osteoporosis using anterior cortex purchase technique. Therefore, the present experimental study may provide spine surgeons selection strategies for optimal fixation device according to patients' bone quality and screw insertion technique. Nevertheless, it should be kept in mind that those recommendations were under axial loading conditions, no conclusion could be made on the other loads applied to screws intraoperatively or postoperatively.

Recently, many surgeons focalized their attention on selection of pedicle screw material, because corrosion of the external implant would be one of the pathogenesis of fixation failure and cause severe side effects on human body [7,9]. As a solution for implant corrosion, several material coating techniques, including PVD/ CVD, micro-arc-oxidation (MAO) and sol-gel coating, were explored to improve corrosion resistance and subsequently reduce harmful ion release [10,12,29]. Furthermore, recent studies reported that coating techniques, such as hydroxyapatite coating and melted polymer sleeve, can be applied to pedicle screws for improving fixation and anchorage [11,30]. However, the effect of screw materials and application of coating techniques were not concerned in present study. Further studies are needed to investigate the influence of different biomaterials and coating techniques on screw pullout biomechanics.

There are several limitations in this study. First, this study was of relatively small sample size of specimens, which might establish bias on the statistical outcomes. Second, we focused on the pullout strength of the screw under axial loading only, which was not representative of entire biomechanical performance of these screws. Finally, this was a biomechanical testing study, and the results based on laminated polyurethane foam specimens and FE models may differ from those experiences under real surgical conditions. Based on the present results, we plan consecutive experimental study using cadaveric human vertebra with different bone quality/BMD under different loading conditions.

제 4 절 결론

The present study demonstrated that the dual-threaded pedicle screw yielded higher and significant lower pullout strength in normal quality and compromised osteoporotic bone, respectively, compared to a conventional pedicle screw. With the trend of statistical significance, the newly designed double dual-threaded pedicle screw exhibited better pullout biomechanics in osteoporotic bone with bicortical bone. FE model analysis is a reliable tool in investigating and predicting biomechanical performance of pedicle screws in terms of pullout strength. The findings could help spine surgeons to select optimal thread design according to patients' bone quality and screw insertion technique considering axial loading condition.

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초 록

이중 나사산 나사는 이미 척추 유합 수술에 많이 사용하고 있지만, 한줄나사와 비교했을 때 그 생체 역학적 성능이 더 우수한 지에 대해서는 아직 논란의 여지가 있다. 본 연구의 목표는 다양한 골질 즉 골다공증과 일반 골질에서 2가지 이중 나사산 나사와 전통적인 한줄 나사의 인장 강도를 비교하고 이중 나사산 나사들의 생역학적 성능을 검토하는 것이다. 다양한 골질에서 나사산 디자인에 따른 척추경 나사못의 인장 강도를 비교 하기 위하여 본 연구에서 4가지 다른 종류의 나사산을 가진 나사를 디자인 하였다. 즉 Type I: 한줄나사, Type II: 두줄나사, Type III: 두줄+한줄 나사, Type IV: 두줄+한줄+두줄 나사. Type I은 전통적인 한줄 나사이고 Type III은 이중 나사산 나사, 그리고 Type IV는 새로 다자인 된 이중 나사산 나사다. 다양한 골질을 simulate하기 위하여 본 연구에서는 폴리우레탄 폼 블록(polyurethane foam block)을 이용하여 5가지 본 블록 (bone block specimen)을 디자인 하였다. 즉 Type A: 일반 해면 골 골질, Type B: 일반 해면 골 골질+ 피질 골 골질, Type C: 골다공증 해면 골 골질, Type D: 골다공증 해면 골 골질+ 피질 골 골질, Type E: 골다공증 해면 골 골질+ 쌍피질 골 골질. 본 블록 Type A, B, C, D에서 척추경 나사 Type I, II, III의 인장강도를 비교하고 본 블록 Type C, E에서 척추경 나사 Type I, II, IV의 인장강도를 비교한다. 동시에 생역학적 실험을 simulate하는 3D Finite element 모델을 사용하여

나사의 인장강도를 추측한다. 생역학적 실험의 결과에서 한줄나사와 비교했을 때 이중 나사산 나사는 일반 해면 골 골질에서 더 우수한 인장 강도를 보였고 골다공증 해면 골 골질에서 통계적으로 차이가 있게 낮은 인장 강도를 보였다. 새로 디자인 된 이중 나사산 나사는 쌍피질 골을 포함 된 골다공증 해면 골에서 더 우수한 인장 강도를 보였다. Finite element 모델에서 추측된 인장강도는 생역학적 실험결과와 잘 상응되여 나사의 인장 강도 등 생역학적 성능을 추적 할때 신뢰될수 있는 방법이다.

주요어 : 척추경 나사못; 인장 강도; 이중 나사산 나사; 폴리 우레탄 폼 블록; Finite element 모델

학 번 : 2016-36832

Table 1. Dimension for all types of screws.

Screw Type	Length (mm)	Outer diameter (mm)	Proximal core diameter (mm)	Distal core diameter (mm)	Pitch (mm)		
					Proximal 1/4	Middle	Distal 1/4
Type I	40	4.5	4.0	2.7	2	2	2
Type II	40	4.5	4.0	2.7	1	1	1
Type III	40	4.5	4.0	2.7	1	2	2
Type IV	40	4.5	4.0	2.7	1	2	1

Table 2. Material propertied in the present FE models.

Component	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio
Osteoporotic cancellous bone	160	23	0.2
Normal cancellous bone	320	137	0.2
Cortical bone	800	1469	0.2
Pedicle screws	4430	110000	0.3

FE: finite element.

Table 3. Pullout strength of all types of screws in various bone specimens.

Bone specimens	Screw types			
	Type I (KN)	Type II (KN)	Type III (KN)	Type IV (KN)
Type A	2.23±0.07	2.38±0.18	2.28±0.13	
Type B	2.65±0.16	2.87±0.13	2.80±0.08	
Type C	1.56±0.23	1.26±0.06	1.32±0.13	0.98±0.15
Type D	1.99±0.11	1.80±0.14	1.82±0.09	
Type E	2.54±0.15	2.68±0.14		2.67±0.07

Four types of screw were, Type I: single thread screw; Type II: double threads screw; Type III: dual-threaded screw, and Type IV: double dual-threaded screw.

Five types of bone specimens were, Type A: cancellous bone; Type B: cancellous bone with cortical bone in upper margin; Type C: osteoporotic cancellous bone; Type D: osteoporotic cancellous bone with cortical bone in upper margin; and Type E: osteoporotic cancellous bone with cortical bone in upper and lower margin.

KN: kilo Newtons

Values are mean ± standard deviation.

Figure 1. Illustration of four types of screws with different thread patterns.

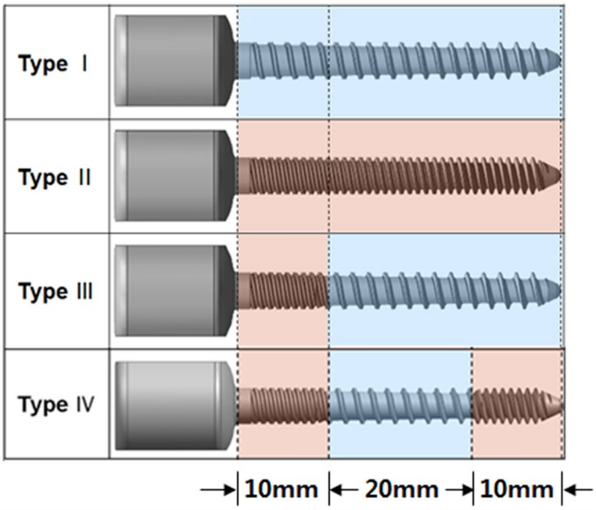
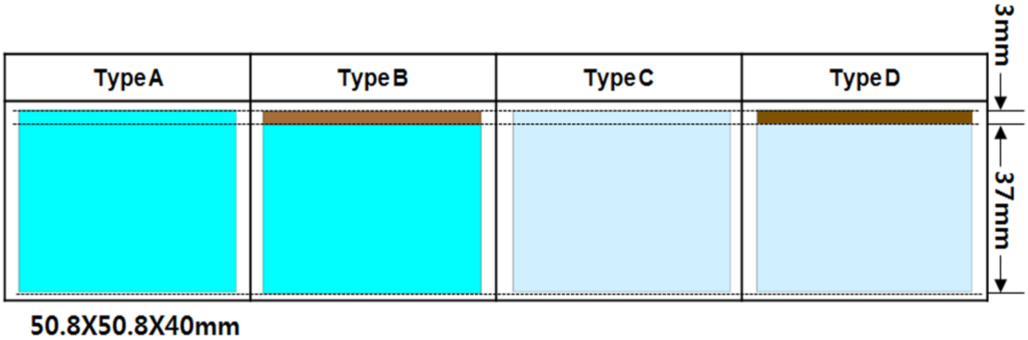


Figure 2. Illustration of bone specimens simulating various bone quality using various density of polyurethane foam blocks. (a) Type A, B, C and D bone specimens and (b) Type C and E bone specimens.

(a)



(b)

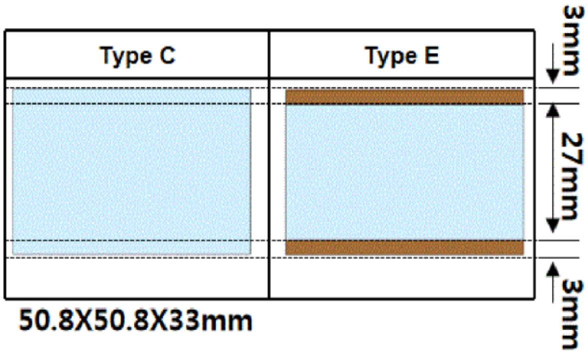


Figure 3. Simulation of screw insertion using anterior cortex purchase technique.

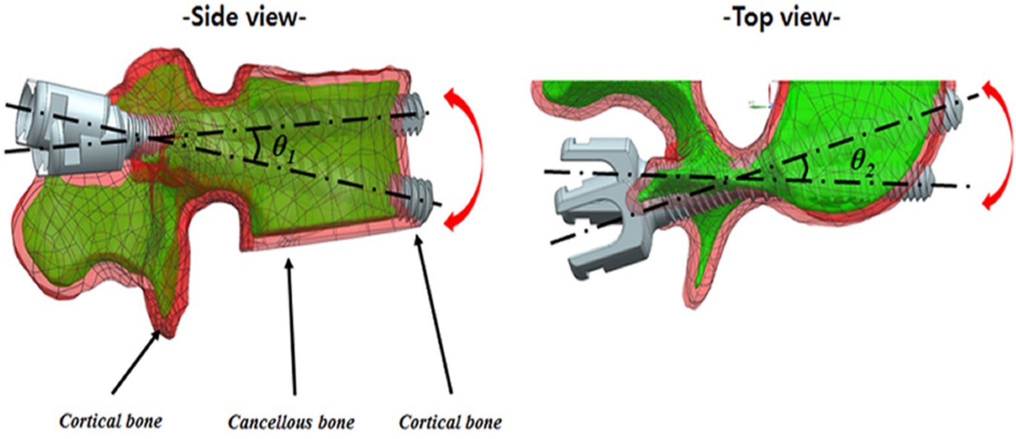


Figure 4. Experimental configuration used for testing the axial pullout strength of pedicle screws.

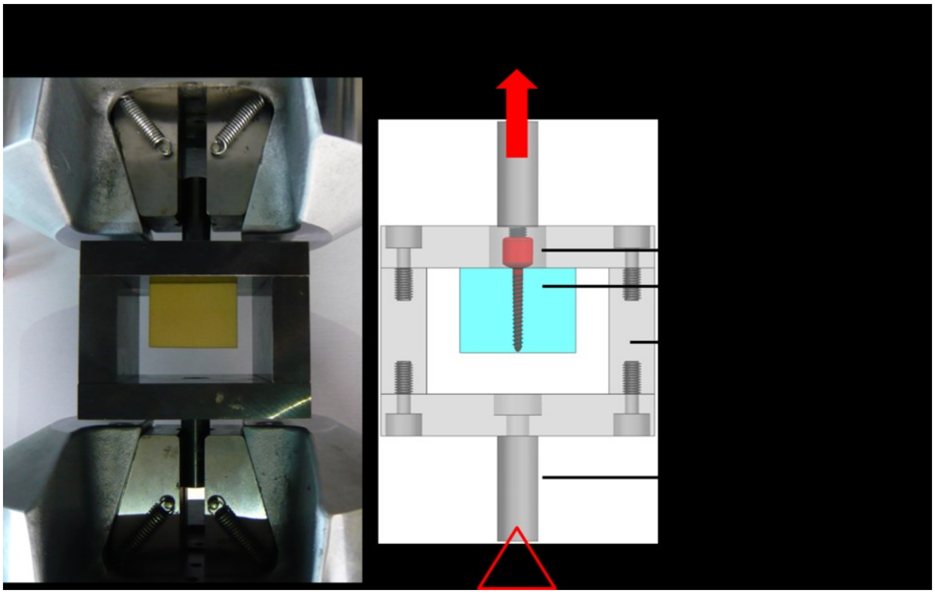
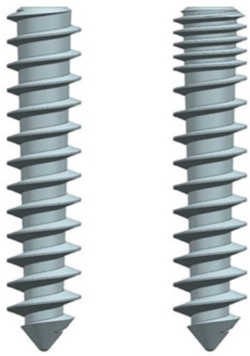


Figure 5. Three−dimensional models of screw thread and bone specimen. (a) thread models of Type I and III screws, and (b) model of bone specimen.

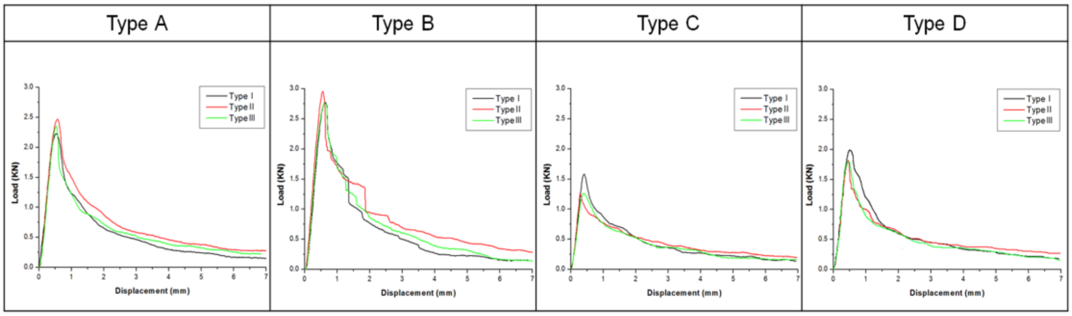


(a)

(b)

Figure 6. Load–displacement curves from axial pullout test. (a) Type I, II and III screws in Type A, B, C and D bone specimens and (b) Type I, II and IV screws in Type C and E bone specimens.

(a)



(b)

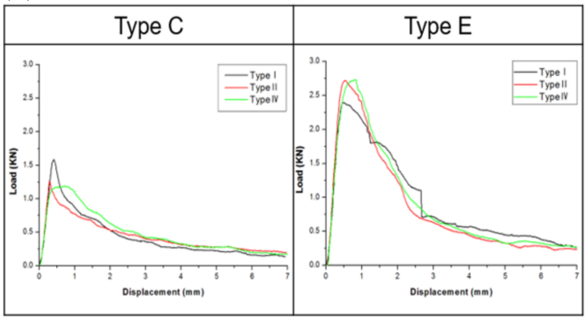
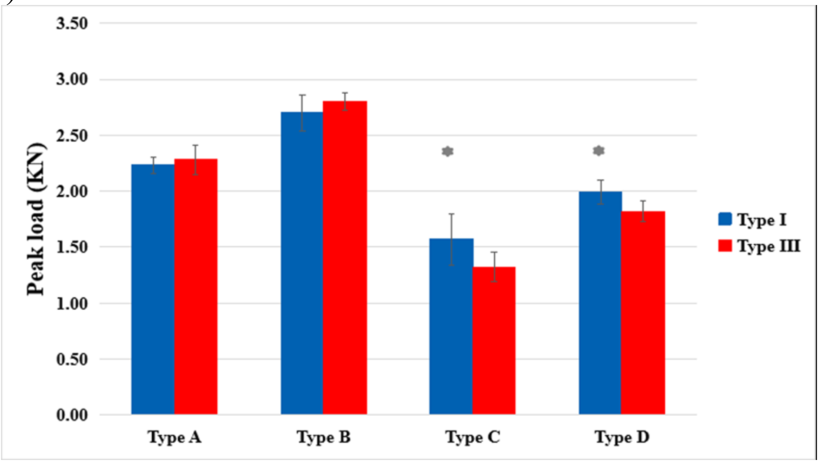
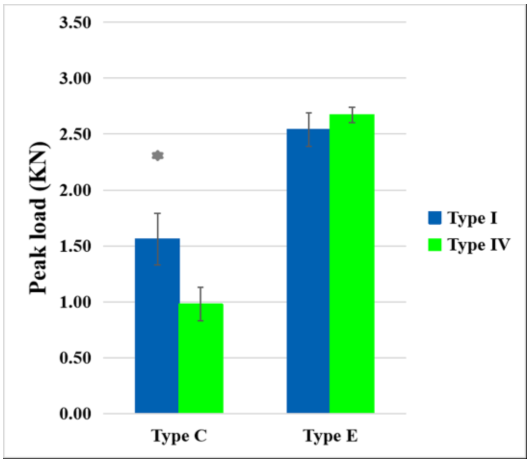


Figure 7. Comparative exhibition of pullout test results, error bar show standard deviation and block contains mean value. (a) comparison between Type I and III screws in Type A, B, C and D bone specimens (P=0.471, P=0.106, P=0.046 and P=0.031, respectively); (b) comparison between Type I and IV screws in Type C and E bone specimens (P=0.006 and P=0.105, respectively); and (c) comparison in normal and osteoporotic bone specimens from FE model analysis.

(a)



(b)



(c)

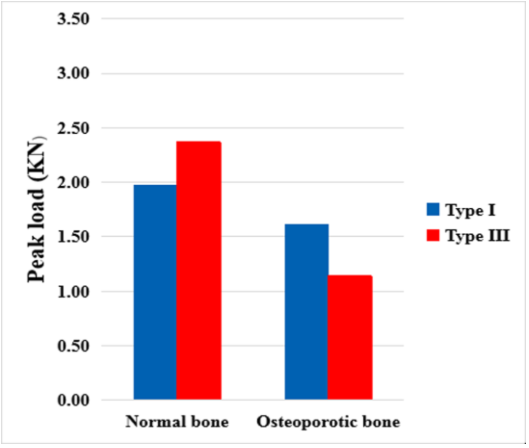

3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Peak load (KN)
Normal bone
Osteoporotic bone
Type I
Type III

Figure 8. Von Mises stress distribution of Type I and III screw in normal bone specimen model.